Millimeter Wave and Laser Satellite Communication

Atmospheric Attenuation Consideration

Paul Christopher

PFC Associates
312 Loudoun St. SW, Leesburg, VA 20175
pfchristop@aol.com

Abstract

High elevation satellite systems and the modest availability extend the attractiveness of millimeter wave communications. Millimeter wave satellite communication in the 72-90 GHz region is indicated to be attractive for most of the Temperate Zone, with a 95% non-rainy condition. Higher frequencies in the 130-170 GHz and 10 micron laser regions are also considered.

Keywords

Satellite Communication; Millimeter Waves; Lasers

Background

The experiments of the Key NASA Lewis Advanced Communications Satellite (ACTS) have expanded satellite communication sharply beyond the 14 GHz region, to attain the high capacity and cost effectiveness near the 30 GHz region (Ka band). The ACTS experiments have been effectively ended in 2000, but the demand for satellite capacity has increased. Fortunately, the Fondazione Ugo Bordoni (FUB) used the invaluable Italsat results to deduce global attenuation results at several important frequencies (Barbaliscia, 1998, 1997). The zenith attenuation maps shown by Barbaliscia, Boumis, and Martellucci for 49.5 and 22.2 GHz 99% non-rainy conditions could be compared to the integrated gaseous attenuation for a satellite link. The excess attenuation implied by the FUB studies was attributed to water vapor and clouds (Christopher, 1999). The attenuation maps at 49.5 and 22.2 GHz were then solved simultaneously for cloud and water vapor attenuation at 22.2 GHz. The simultaneous solution was done at all points on the map, allowing a functional description of zenith attenuation as a function of longitude, latitude, and frequency for frequencies in the 6 to 100 GHz range. This attenuation function indicated that satellites with high elevation angles (Christopher, 2000; Draim, 2002) would offer promising performance for frequencies greater than 40 GHz in much of the Temperate Zone. Frequencies greater than 80 GHz were seen to be possible for latitudes greater than 50N.

The 99% non-rainy attenuation results for 72 GHz may be seen in Fig 1-1. The results are shown as zenith attenuation (dB) v. longitude (LON) and latitude (LAT).

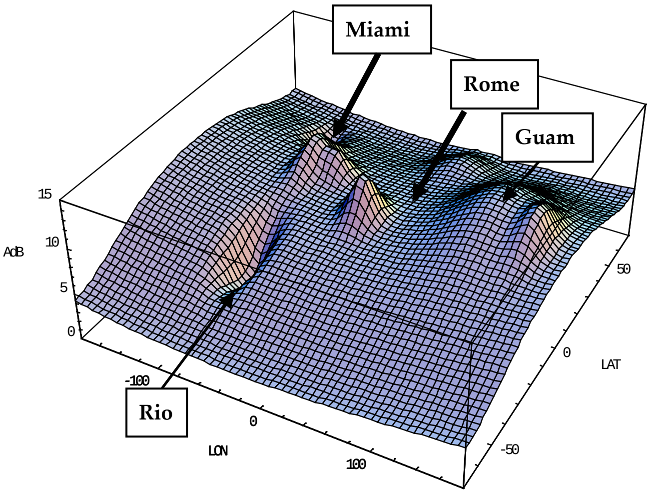

FIG 1-1 ZENITH ATTENUATION AT 72 GHz 99%AVAILABILITY MATHEMATICA Mar09-ZEN.nb

We attempt to approach the favorable zenith attenuation here, with the aid of high elevation Molniya satellites coordinated with antipodal geostationary satellites. Molniya systems, attractive, may be good alternatives *or even replacements* for geostationary systems (Christopher, 2008). Selected Brandon Molniya eccentricity (e=0.722) is characterized by simplicity, low cost, high gain ground antennas.

The attenuation equations are long and may be conveniently represented as a Mathematica program. A shortened equation for 95% availability is in the Appendix. It can also be expressed in Fortran or C.

The 99% non-rainy attenuation here is relaxed to 95%

with the aid of attenuation probabilities and an analysis (Christopher, 2003) to examine if the 72-100 GHz region might be widely useful in the Temperate Zone has been conducted. It is a function of latitude, longitude, and frequency useful in the 6 GHz to 100 GHz region, with some utility outside the region.

The zenith attenuation function can also be seen as global maps for constant exceedance probability. The relatively intense 99% non-rainy availability attenuation is indicated in Fig. 1-1.

Zenith attenuation contours are seen to be notably lower, and less than 5 dB at 95% availability for large parts of the temperate zone on Fig. 1-2.

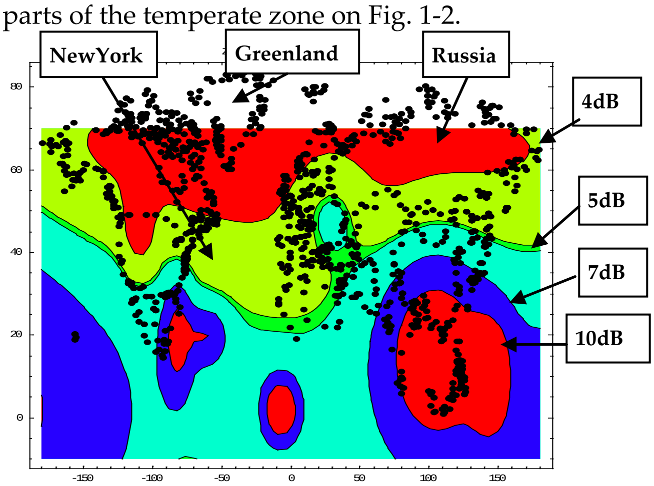

FIG. 1-2 72 GHz ZENITH ATTENUATION CONTOURS AT 95 % AVAILABILITY

High Elevation Molniya Systems

The zenith attenuation of the prior section must be weighted by the atmospheric path length, or closely as Cosecant [elevation angle]. Zenith attenuation near 5 dB at New York for 90 GHz in Fig. 1-2 would be doubled to 10 dB for a 30 degree elevation to a satellite. Some geosynchronous satellites do indeed present 30 degree elevation to New York, so 10 dB might be foreseeable for a 90 GHz New York link to a GEO. This attenuation might be debilitating for a millimeter wave system, and it is questioned if there could be any relief from high elevation systems.

In the mid 60s, the Soviets recognized another outstanding way to get good satellite coverage at high latitudes. They used an inclined elliptic satellite to get several hours of uninterrupted coverage at Moscow. Fig. 2-1 shows 1 hour snapshots of the 12 hour orbit in a ground coordinate system.

Exhaustive elevation computation for all time and locations yields the elevation probability density function (pdf) as an analytic function of Latitude (LAT) (Eq 2-1). It is seen in Fig. 2-2.

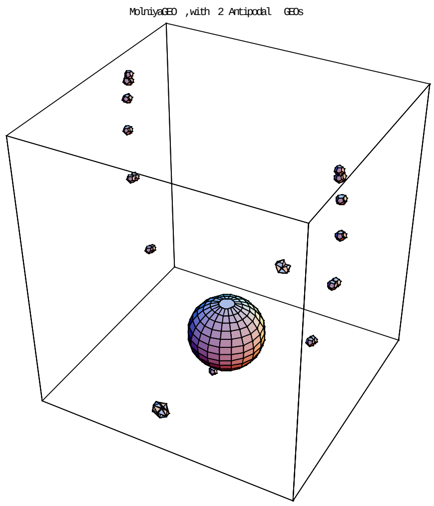

FIG. 2-1 COMPLEMENTARY MOLNIYA AND GEOSYNCHRONOUS SATELLITES (MolniyaGEO Constellation) WITH 3 MOLNIYA, 2 GEO

$$p(x)=\frac{e^{-\frac{\left(-47.0509+0.165865\,LAT+0.0051249\,LAT^{2}-0.00052000\,LAT^{3}+5.22822\times10^{-6}\,LAT^{4}+x\right)^{2}}{2\left(-160.041+181.722\,e^{-\frac{LAT^{2}}{900}}-0.776901\,LAT+0.270942\,LAT^{2}-0.00526509\,LAT^{3}+0.00029238\,LAT^{4}\right)^{2}}}}{\left(-160.041+181.722\,e^{-\frac{LAT^{2}}{900}}-0.776901\,LAT+0.270942\,LAT^{2}-0.00526509\,LAT^{3}+0.00029238\,LAT^{4}\right)\sqrt{2\pi}} \quad (2\text{-}1)$$

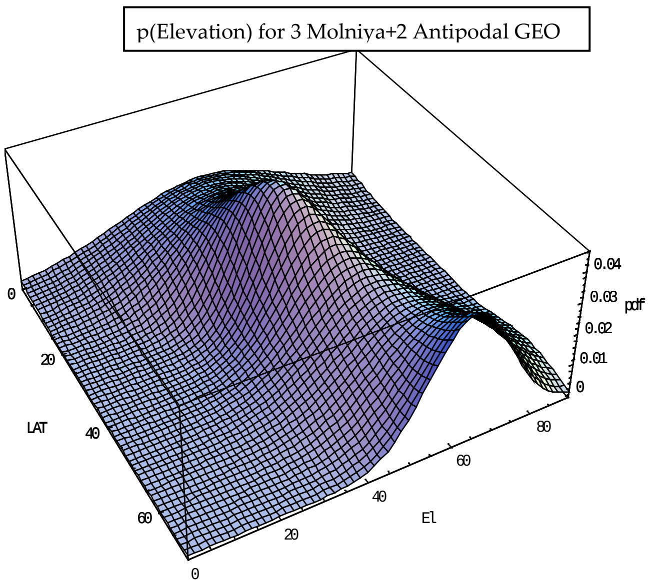

FIG. 2-2 MOLNIYAGEO ELEVATION PDF v. LATITUDE, ELEVATION

Average elevation is close to 60 degrees at 60N, and more importantly, high elevation as 50 degrees is seen at New York City near 40 North. The average cosecant [elevation] at each latitude can be found, and multiplied by zenith attenuation to find representatively higher satellite attenuation. The satellite attenuation south of 20N would be clearly higher than the zenith attenuation: 60% extra attenuation [dB] would be expected on the best MolniyaGEO path at 20N. The most useful parts of the Temperate Zone would include regions between 30N to 60N. It is noted that New York City and Rome are near 40N.

The pdf (Eq 2-1) will imply satellite attenuation higher than zenith attenuation of Fig. 1-3.

The combination is shown as Fig. 2-3. New York City is seen to retain the modest 6 dB attenuation with the typically high elevation near 50 degrees.

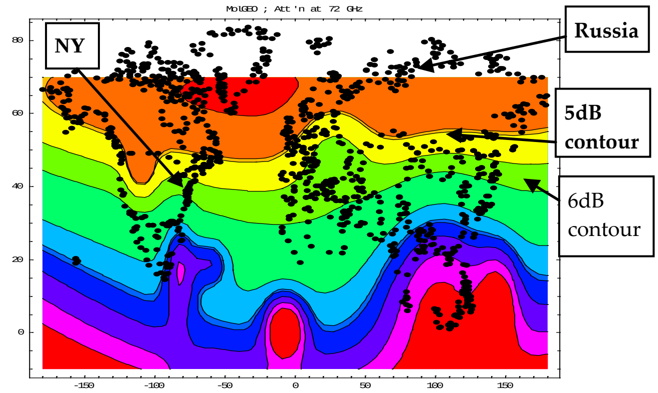

FIGURE 2-3 ATTENUATION CONTOURS FOR MOLNIYAGEO CONSTELLATION; 72GHz, 95% Mathematica Mar209--MolGEO.nb.

The 72 GHz results can also be extended to give other satellite constellations, higher frequencies and other availabilities. Geostationary satellites would present compromised attenuation as Fig. 2-4 indicates. Fig. 2-5 shows the contours of Fig. 2-4.

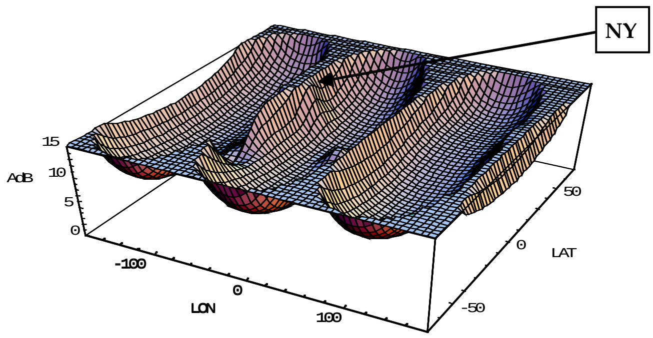

FIG. 2-4 GEOSTATIONARY ATTENUATION AT 72 GHz, 95% AVAILABILITY GEOs AT 105E, 225E, 15W Mar09---GEO.nb

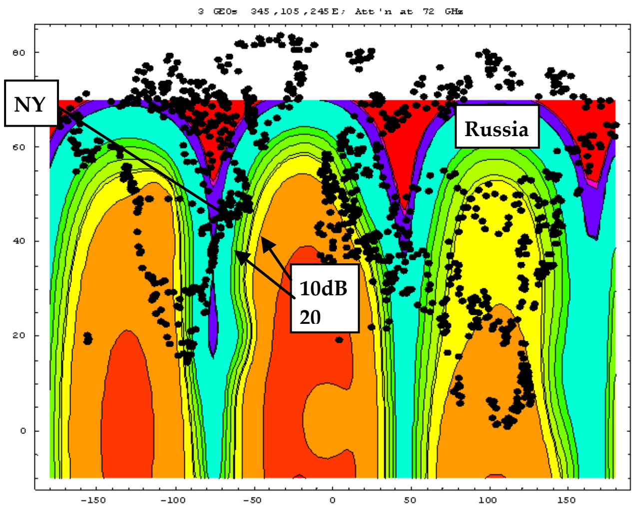

FIG. 2-5 GEOSTATIONARY ATTENUATION CONTOURS AT 72 GHz, 95% GEOs at 105E, 225E, 15W

Higher Frequencies

Frequencies higher than 72 GHz will also be recognized as valuable, not only because of increasing frequency allocation problems, but also because they can offer cost effectiveness with small ground antennas. For example, 85-90 GHz may offer reasonable losses in the Temperate zone with the proper choice of satellites. The 130-160 GHz region has also been mentioned as interesting. Key 120-170 GHz clear air observations at Lincoln Lab by Rosenberg have been available since the early '60s. We fit those observations with a functional relation at the 118 GHz resonance and the 130-170 GHz region and the cloud attenuation. The 95% attenuation is indicated near 12 dB in Fig. 2-4.

These relatively high attenuations at reasonable availability might be declined at lower availability, as in Fig. 2-6.

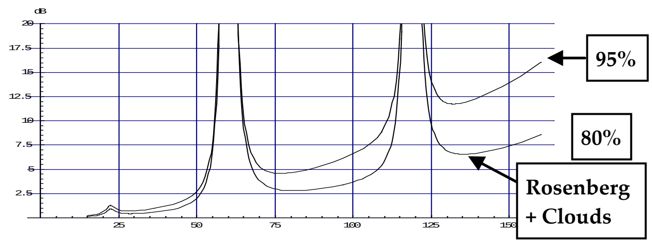

FIG 2-6 ZENITH ATTENUATION AT NY CITY, 15-170 GHz

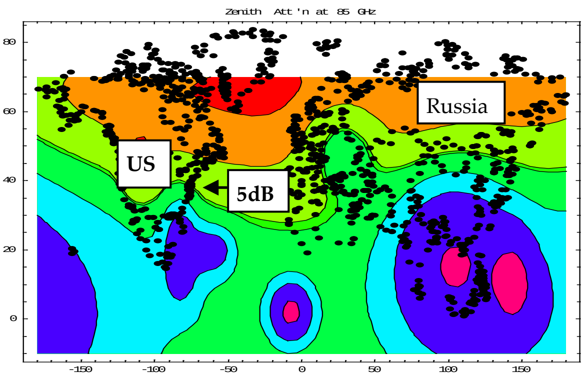

FIG. 2-7 WORLDWIDE ZENITH ATTENUATION FOR 85 GHZ, 95% AVAILABILITY CONTOURS -3,4,5,6,7,9dB MATHEMATICA Mar209Feb2309---85GHzZENb.nb

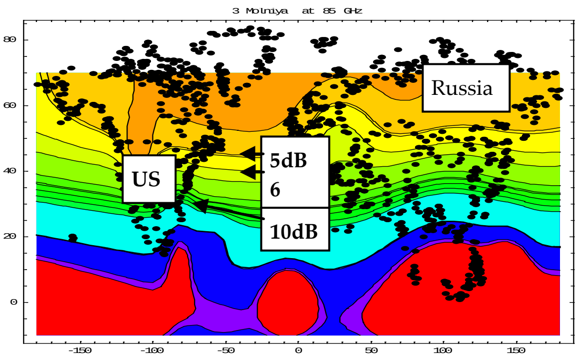

FIG. 2-8 WORLDWIDE MOLNIYA ATTENUATION FOR 85 GHz, 95% AVAILABILITY CONTOURS -3, 4,5,6,7,9,10, 11-dB Mar209Feb2309---85GHzMOLb.nb

The attractive zenith attenuation of 85GHz is seen as Fig 2-7.

The 5 dB contour is seen to shift northward in Fig. 2-8 to Labrador- Seattle, and the 10 dB contour extends from San Diego to S. Carolina.

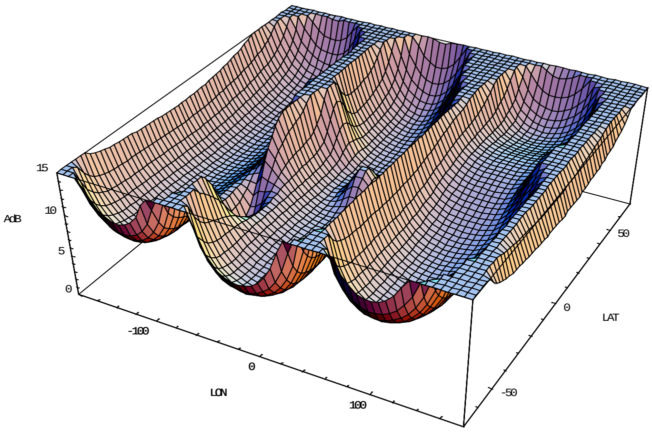

FIG. 2-9 85 GHZ ATTENUATION FOR 3 GEOs AT 345E, 105E, 245E MATHEMATICA Feb240985GHzGEOb.nb

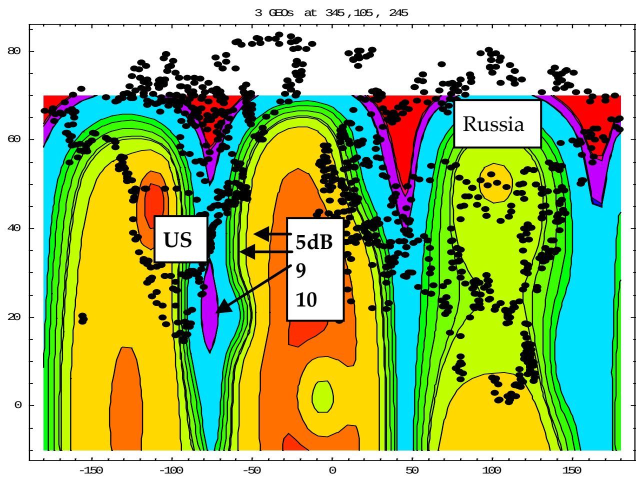

FIG. 2-10 85 GHZ ATTENUATION CONTOURS FOR GEOs AT 345E, 105E, 245E CONTOURS-3,4,5,6,7,9,10, 11-dB Mar209Feb240985GHzGEOb.nb

The corresponding attenuation for three GEOs at 345E, 105E and 245E may also be compared with the Molniya attenuation. Fig. 2-9 gives a 3D plot of attenuation at 85 GHz and 95% non-rainy availability.

The attenuation contours for the GEOs can clarify the atmospheric loss, as Fig. 2-10.

The 9-10 dB contours are now on the whole eastern seaboard south of Washington. In contrast (Fig. 2-8), the entire Temperate Zone north of Atlanta benefits from the 3 Molniya, and is indicated as less than 9 dB.

A combination of 3 Molniya and 2 antipodal GEOs can offer high elevation over the entire Northern Hemisphere. The pdf for the combination of Molniya and 2 GEOs (Sec 1) is used, and the 85 GHz contours are seen as Fig. 2-11. The 5 dB contour is indicated as Labrador-Southern England, and the 10 dB contour is pushed southward close to Daytona.

The 130-160 GHz band is also interesting. Fig 2-12 shows zenith attenuation at 140 GHz.

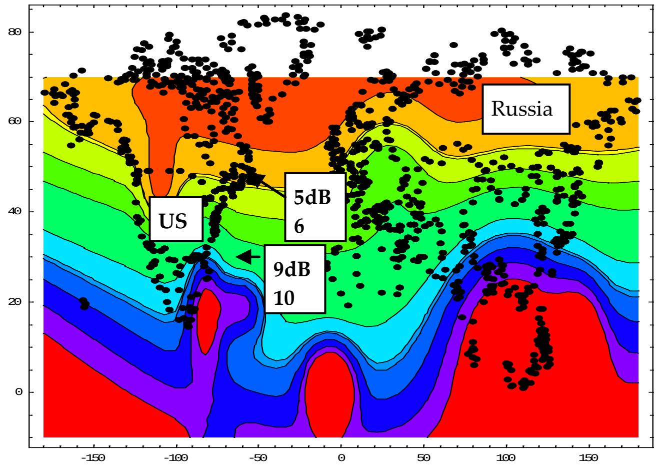

FIG. 2-11 85 GHz ATTENUATION CONTOURS FOR 3 MOLNIYA & 2 ANTIPODAL GEOs CONTOURS-3,4,5,6,7,9,10, 11-dB MATHEMATICA Feb2409—MolGEO85GHz.nb

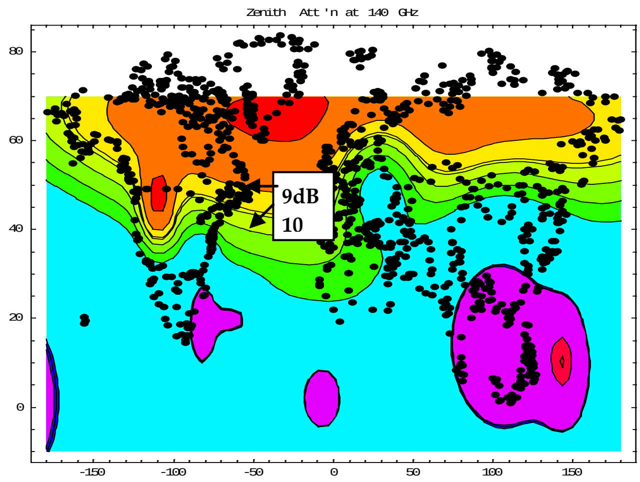

FIG. 2-12 ZENITH ATTENUATION CONTOURS AT 140 GHz CONTOURS-3,4,**5**,6,7,9,**10**, 11-20dB MATHEMATICA Mar209—ZEN140GHz.nb

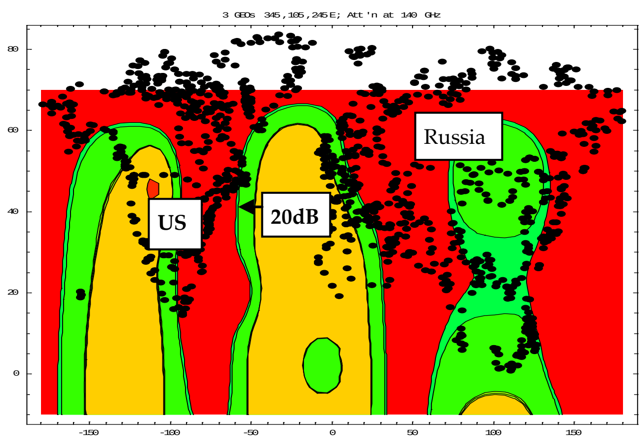

FIG. 2-13 GEO ATTENUATION CONTOURS AT 140 GHz CONTOURS-3,4,5,6,7,9,10, 11-20d MATHEMATICA Mar209—GEO140GHz.nb

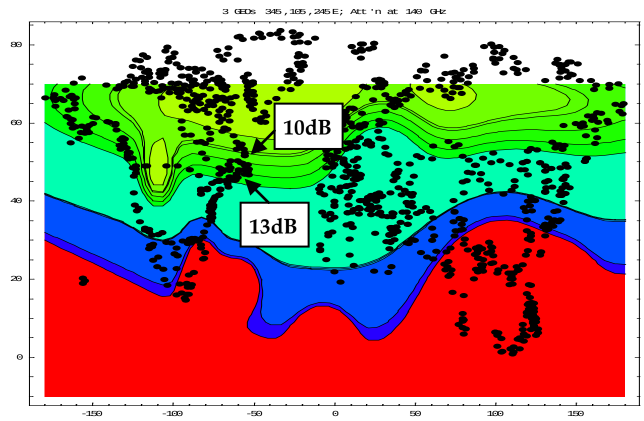

FIG. 2-14 MolniyaGEO ATTENUATION CONTOURS AT 140 GHz CONTOURS-3,4,5,6,7,9,10, 11-20dB MATHEMATICA Mar209—MolGEO140GHz.nb

The relatively high 140 GHz implies high penalties for GEO satellites (Fig. 2-13), with 20 dB at Labrador and Boston approaches 42 dB. In contrast, the 3 Molniya/2 antipodal GEO attenuation at Boston implies 14.7 dB (Fig. 2-14).

Ten Micron Laser Attenuation

Laser communication is attractive for relatively high data rate, with compact low cost transmitters and receivers. Unfortunately, it suffers from higher atmospheric attenuation than millimeter wave attenuation. Key research at Bell Labs (Chu, 1968) showed the advantages of 10.6 microns for low cloud attenuation.

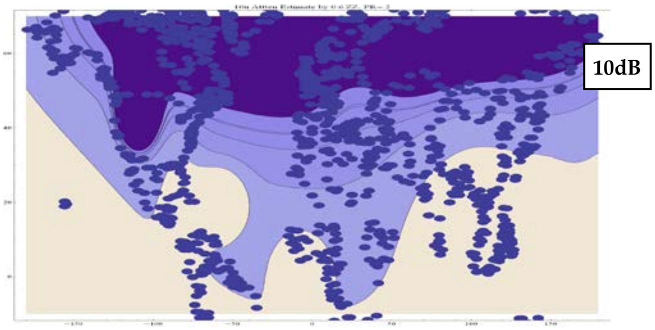

FIG. 3-1 10 MICRON CLOUD ATTENUATION, WITH LOW ATTENUATION IN ROCKIES MATHEMATICA Jan8—lrev2.nb

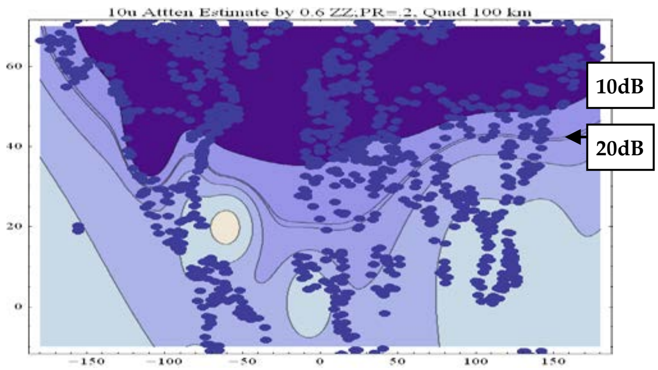

FIG. 3-2 TEN MICRON ZENITH ATTENUATION WITH 100 KM QUAD DIVERSITY MATHEMATICA Jan8—lrev2.nb

Ten micron wavelengths offer special advantages for lasers to overcome cloud attenuation. The Barbaliscia results allow cloud water content to be derived, and attenuation to be estimated for ten micron laser communication as Fig 3-1. The 10 dB attenuation contour is near Boston for 80% availability. Widely spaced diversity can also relieve attenuation at ground receivers (Boldyrev,1971). Even sharper relief is indicated for ground receivers arranged in a square array (quad diversity) as Fig. 3-2. The 10 dB contour then moves south to New York, and the 20 dB contour near the Carolinas.

The 3D representation of 10 micron attenuation can also be helpful, as Fig. 3-3 indicates the 20 dB contour running through southern Virginia for quad diversity and 25 km on each side of the square.

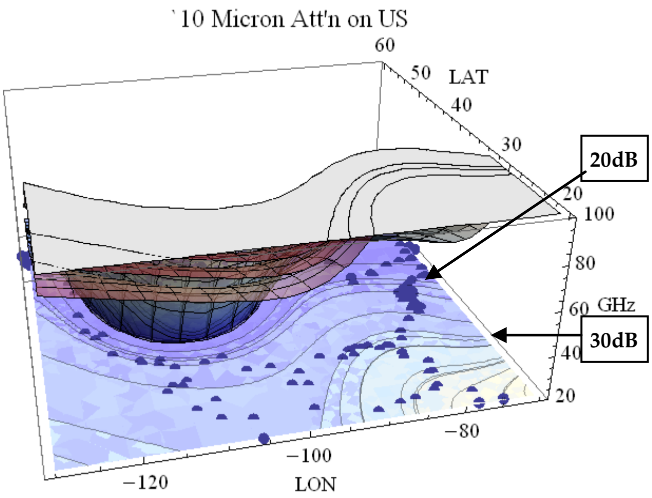

FIG. 3-3 TEN MICRON ZENITH ATTENUATION WITH 25 KM QUAD DIVERSITY MATHEMATICA Jan8—tabl5x.nb

Conclusions

The modest attenuation at 95% availability and high elevation Molniya satellite systems have been emphasized, for good millimeter wave performance.

The 95% non-rainy condition was indicated here to allow 75-90 GHz frequencies to be used advantageously throughout much of the Temperate Zone. New York was shown as the modest 5 dB zenith attenuation at 85 GHz, or approaching 7 dB with favorable Molniya satellites (Fig 2-8}. The 130-170 GHz band offers new spectrum advantages, but cloud cover would give notably higher attenuation than the 72-100 GHz region. Laser communication is attractive in Section 3, but with even higher cloud attenuation.

ACKNOWLEDGEMENTS

The late W. T. Brandon was the key organizer of Ka

band projects at the Mitre Corp. in the early 1980s. He and Dr. P.K. Lee gave valuable insights into the utility of Ka band systems, and Dr. Lee recognized the value of 140 GHz in fair weather systems.

An anonymous reviewer offered key clarifications and improvements for the paper.

SELECTED REFERENCES

Barbaliscia, F., Boumis, M., Martellucci, A., "Characterization of Atmospheric Attenuation in the Absence of Rain in Europe in SHF/EHF Bands for VSAT Satcom Systems Applications," Ka Band Conference, Sorrento, Italy, Sept. 1997.

Barbaliscia, F., Boumis, M., Martellucci, A., "World Wide Maps of Non Rainy Attenuation for -Margin Satcom Systems Operating in SHF/EHF Bands," Ka Band Conference, Sorrento, Italy, Sept. 1998.

Boldyrev and Tulupov, Cloud Correlation Function, COSPAR Space Research XI, Leningrad USSR 20-29 May 1970, Vol. 1 Akademie-Verlag Berlin, 1971.

Christopher, Paul, "World Wide Millimeter Wave Attenuation Functions from Barbaliscia's 49/22 GHz Observations," Ka Band Conference, Taormina, Sicily, Oct. 1999.

Christopher, Paul, "Satellite Constellations for Ka Band Communication," Ka Band Conference, Cleveland, Ohio, June 2000.

Christopher, Paul, "Millimeter Waves for Broadband Satellite Communication," Proc. Ka and Broadband Conference, Isle of Ischia, Italy, Sept. 2003.

Christopher, P., "Molniya System Alternatives for Geostationary Satellite Systems-," Ka and Broadband Conference, Matera, Italy, September, 2008.

Chu, T.S. and Hogg, D.C., "Effects of Precipitation at 0.63, 3.5, and 10.6 Microns", Bell System Technical Journal, May-June 1968.

Draim, John E., Christopher, Paul, "Reducing Extra-High Frequency Attenuation by Using COBRA Elliptical Orbit Systems," AIAA Proceedings Paper AIAA-2002-1907, Montreal, June 2002.

Trott, Michael, *The Mathematica Guidebook for Symbolics*, New York, NY; Springer 2006.

Appendix Short Form for 90 GHz Zenith Attenuation

The long form (6) for zenith attenuation may be chopped with the aid of Mathematica (Trott, 2006) at 90 GHz and 95% availability to yield (A-1) and Fig. A-1.

$$\begin{aligned}\mathrm{ZZchop90} = {} & 0.614769 - 3.30579 \Big(0.1 - 2.99573 \Big(3.3511\times10^{-8}\,\mathrm{LAT}^4 + 1.63608\times10^{-7}\,\mathrm{LAT}^3 + (6.07688\times10^{-8}\,\mathrm{LON} - 0.000329026)\,\mathrm{LAT}^2 + 5.74427\times10^{-10}\,(\mathrm{LON} - 2029.74) \\ & (\mathrm{LON} - 147.348)\,\mathrm{LAT} + 0.279404\, e^{\frac{1}{200}(-(\mathrm{LAT}-10)^2-(\mathrm{LON}-145)^2)} + 0.382293\, e^{\frac{-9(\mathrm{LAT}-18)^2-4(\mathrm{LON}-102)^2}{7200}} + \\ & 0.217021\, e^{\frac{1}{800}(-4(\mathrm{LAT}-52)^2-(\mathrm{LON}-28)^2)} - 0.470602\, e^{\frac{-100\,\mathrm{LAT}^2-\mathrm{LON}^2}{180000}} + 0.460267\, e^{-\frac{1}{72}(\mathrm{LAT}-2)^2-\frac{1}{200}(\mathrm{LON}+7)^2} + 0.264303\, e^{\frac{1}{200}(-4(\mathrm{LAT}-20)^2-(\mathrm{LON}+60)^2)} - \\ & 0.421739\, e^{\frac{1}{200}(-(\mathrm{LAT}+28)^2-(\mathrm{LON}+77)^2)} + 0.317213\, e^{-\frac{1}{200}(\mathrm{LAT}-20)^2-\frac{1}{128}(\mathrm{LON}+82)^2} - 0.200957\, e^{-\frac{1}{98}(\mathrm{LAT}-45)^2-\frac{1}{128}(\mathrm{LON}+110)^2}\Big)\Big)\end{aligned} \tag{A-1}$$

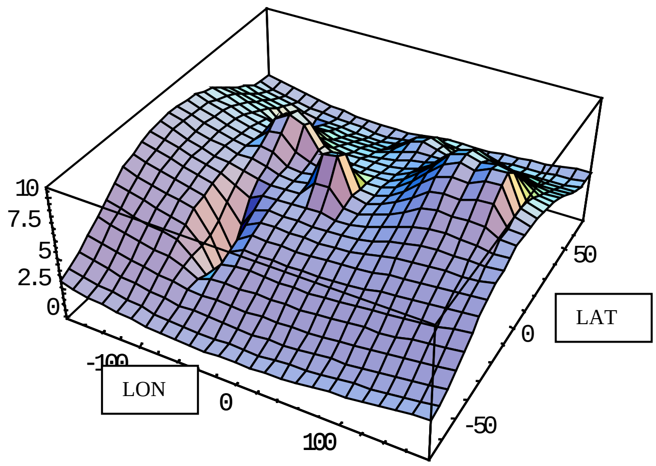

FIG. A-1 SHORT FORM FOR 90 GHz ZENITH ATTENUATION (DB) V. LONGITUDE (DEG E), LATITUDE